# High G MEMS IMUs & Common Guidance


*Presented by*
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## "Smart" Ideas For Overwhelming Firepower

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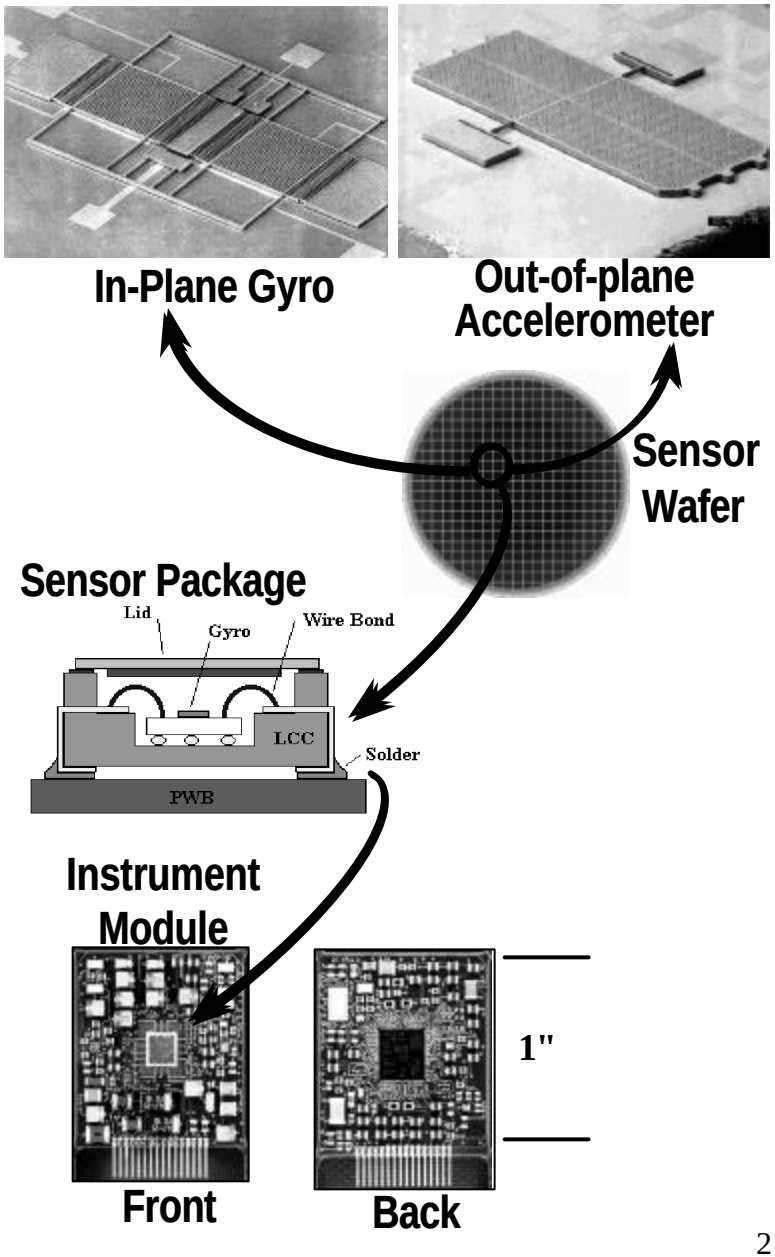
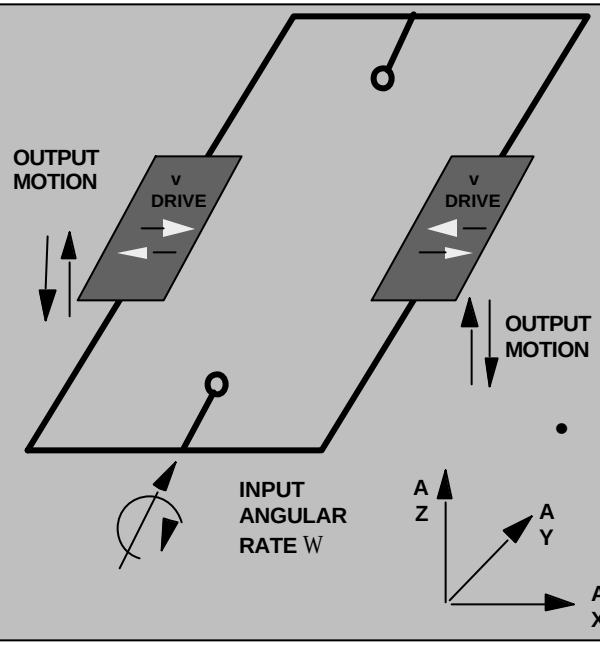
# Micro Electro-Mechanical Systems (MEMS)

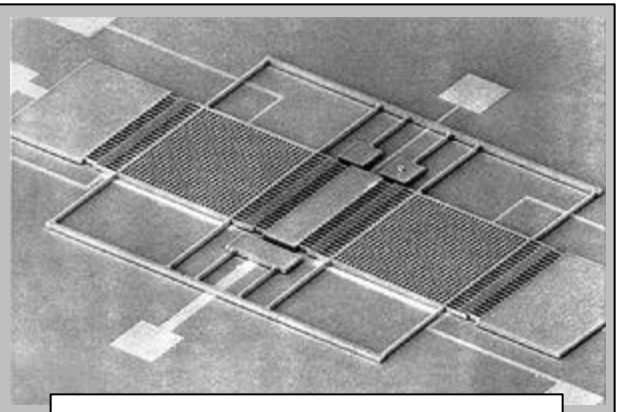
**MEMS are miniature mechanical structures that are produced by commercial integrated circuit (IC) manufacturing like processes. MEMS based sensors are defined as integrated micro sensing devices or systems, which combine electrical and mechanical components on the same silicon chip. This provides a very small, inherently G hardenable device, at low cost due to the economy of scale in the IC manufacturing process. These MEMS sensors can be constructed in tightly integrated arrays of accelerometers and rate-sensing gyroscopes which provides a low-cost, extremely small, high performance, Inertial Measurement Unit (IMU) suitable for tactical projectile / missile guidance and other DoD applications.**



# Tuning Fork Gyroscope (TFG) Physical Characteristics

- **Material** ➢ **Single crystal Si on Pyrex**
- **Operating frequency** ➢ **~ 20 kHz**
- **Proof mass size** ➢ **400 mm X 450 mm X 10 mm (2.7 X $10^{-9}$ kg)**
- **Sensor drive** ➢ **electrostatic**
- **Pick-off** ➢ **capacitive**
- **Motor amplitude** ➢ **10 mm peak**
- **Motor velocity** ➢ **1.6 m/s**



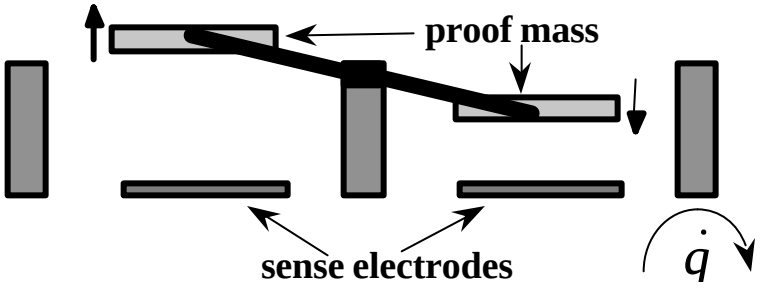
Tuning fork gyro (circa 1992)

- **Operating Principle**
  - **Newton's Laws in a Rotating Frame**

$$\frac{md^2r}{dt^2} = F - m\Omega \times (\Omega \times r) - 2m\Omega \times \frac{dr}{dt} - \frac{md\,\Omega}{dt} \times r$$

**Courtesy of C.S. Draper Labs**

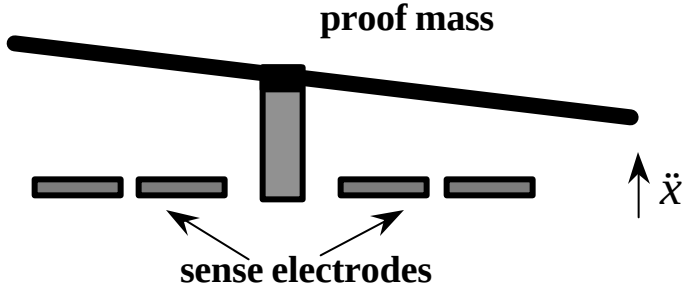
# Instrumentation Challenges - MEMS Wonders




**TFG Proof Mass Motion for Input Rate**

- For a TFG, a 1 r/s input rate results in:
  - **a Coriolis Force of approximately $9X10^{-8}$ N**
  - **$1X10^{-9}$ m of peak motion long the sense axis**
  - **a 3 attofarad ($10^{-18}$) peak change in capacitance**
  - **Charge generation of 15,000 to 65,000 electrons**

- **For an Accelerometer, a 1 g acceleration results in:**
  - **a delta angle of $7X10^{-5}$ radians**
  - **about $3X10^{-8}$ meters change in sense gap**
  - **a 12 femtofarad ($10^{-15}$) peak change in capacitance**
  - **Charge generation of 22,500 electrons**




**Pend. Accel Proof Mass Motion for Input Accel**

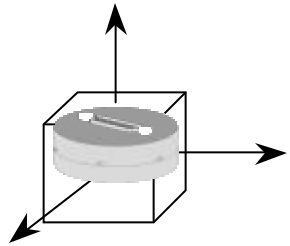
- **Dynamic Ranges**
  - **Gyro (131 dB)**
    - **1000 º/s to 1 º /hr**
  - **Accelerometer (104 dB)**
    - **15 gs to 100 mgs**

**Require instrumentation capable of resolving:**

- **motions of $4.8X10^{-15}$ m for the gyro and $3.0\ X10^{-12}$ m for the accelerometer**
- **a 1 º/hr rate or about 0.25 electrons per cycle of motor motion**
- **a 100 mg acceleration or about 22.5 electrons per carrier cycle**

**Courtesy of C.S. Draper Labs**

# Inertial Systems



- **Inertial Sensor Arrays (ISA) Consist of 3 Gyroscopes and 3 Accelerometers which Measure Changes in 3-D Space**
- **IMUs Consist of an ISA and a µProcessor, Providing 3-D Changes in Angle & Velocity.**
  - **Accuracy Degrades as Function of Time from initialization.**
- **An Inertial Navigation System (INS) is Comprised of an IMU and a Navigation Computer Running Guidance Laws, Providing a 3-D Position, Velocity, & Angular Acceleration.**
  - **Typically Used to Navigate Aircraft, Missiles, Vehicles, Spacecraft & Ships**
- **GPS can be Integrated with an ISA, IMU or INS to Improve Accuracy (GPS/ISA, GPS/IMU or GPS/INS) add Jamming Resistance**

# Why MEMS?

***Solid State Insertion Has Dramatically Reduced Size and Cost, but MEMS offers further reductions***

**CAINS II**
**AN/ASN-139 (RLG)**

| | |
|---|---|
| DRIFT RATE: | 0.001 deg/hr |
| SURVIVABILITY: | 50 G |
| WEIGHT: | 47.3 lbs. |
| VOLUME: | 1418 cu in |
| POWER: | 141 Watts |
| COST: | $100K |


**GPS GUIDANCE PACKAGE (GGP) (FOG)**

| | |
|---|---|
| DRIFT RATE: | 0.01 deg/hr |
| SURVIVABILITY: | 50 G |
| WEIGHT: | 7-10 lbs. |
| VOLUME: | 170 cu in |
| POWER: | 30 Watts |
| COST GOAL: | ~$15K |

***µSCIRAS – Excalibur (XM982) (MEMS)***

| | |
|---|---|
| DRIFT RATE: | 75 deg/hr |
| SURVIVABILITY: | 15500 G |
| WEIGHT: | 0.65 lbs. |
| VOLUME: | 4 cu in |
| POWER: | 5 Watts |
| COST GOAL: | $2.2K |

**(In Development)**

**High G, Low Cost, MEMS IMU**

| | |
|---|---|
| DRIFT RATE: | 1 deg/hr |
| SURVIVABILITY: | > 20000 G |
| WEIGHT: | < 0.2 lbs. |
| VOLUME: | 2 cu in |
| POWER: | < 1 Watts |
| COST GOAL: | < $1.2K |

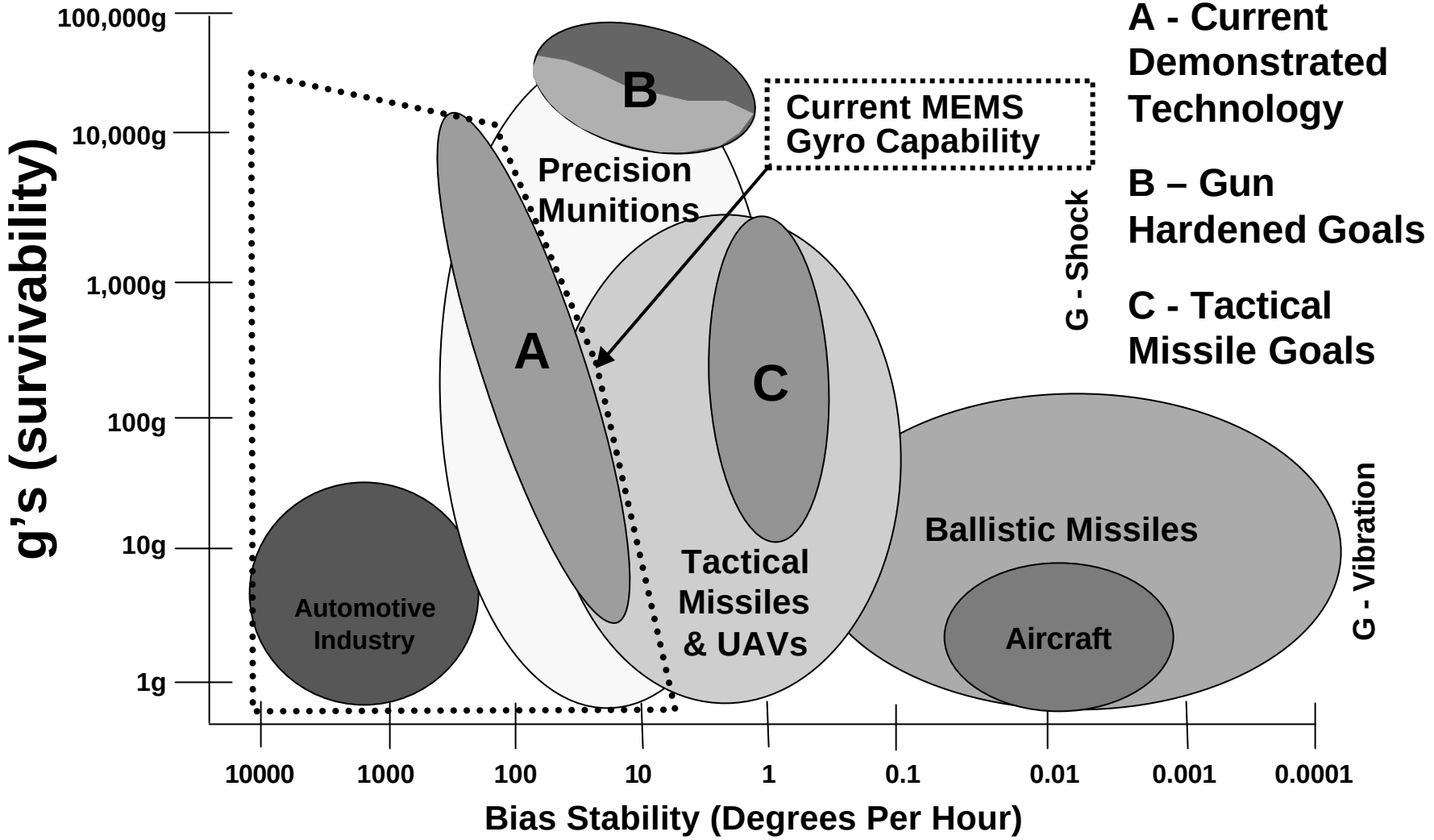
**(STO/DTO/HTI)**

**Only micromachining technology, through batch fabrication, has the potential to meet the following goals:**

- Low cost (the driving factor for many Tri-Service applications)
- Low volume & weight
- Low power consumption
- Tactical-grade performance
- Low maintenance requirements
- High reliability and long life


Photo Courtesy of Conrad Mueller, Honeywell

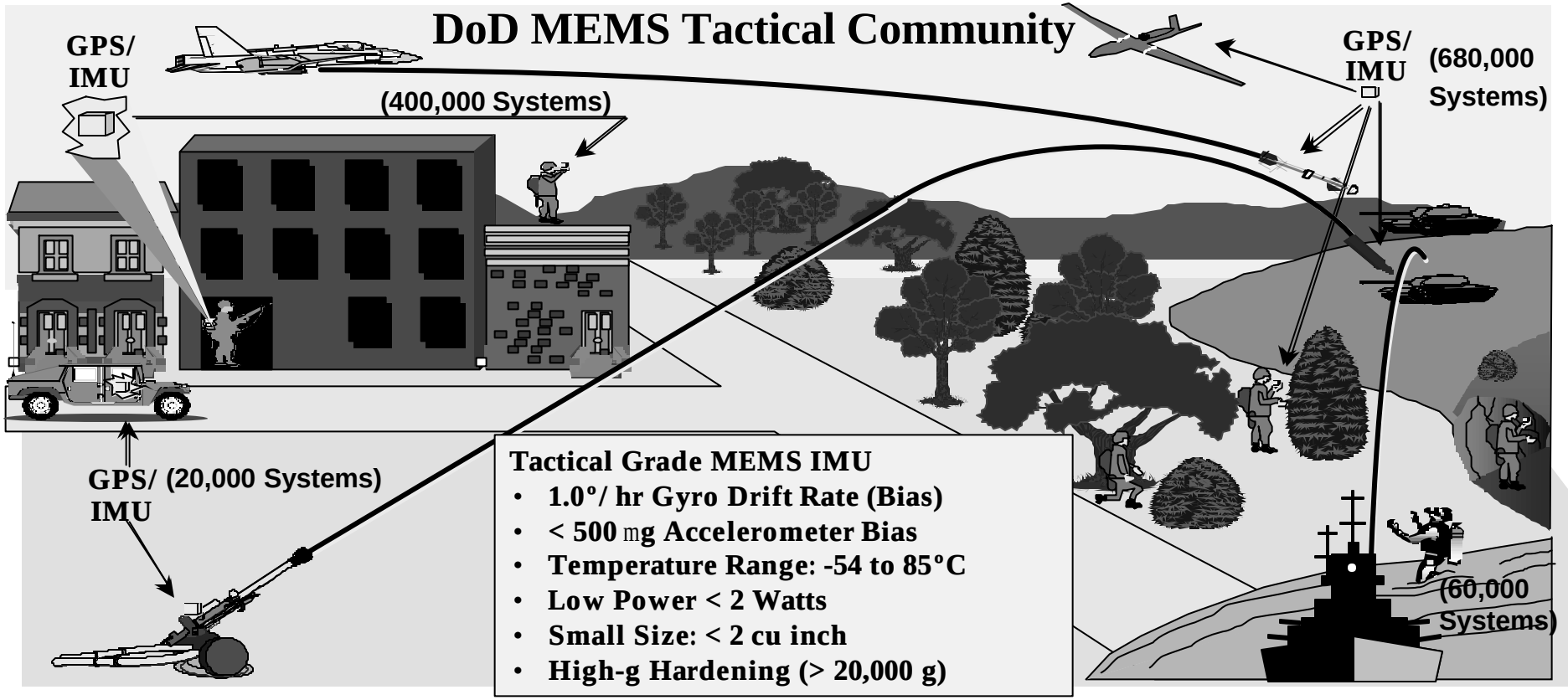
# MEMS Gyro Application Regimes




***Currently Identified Two Distinct Voids in MEMS Capability***

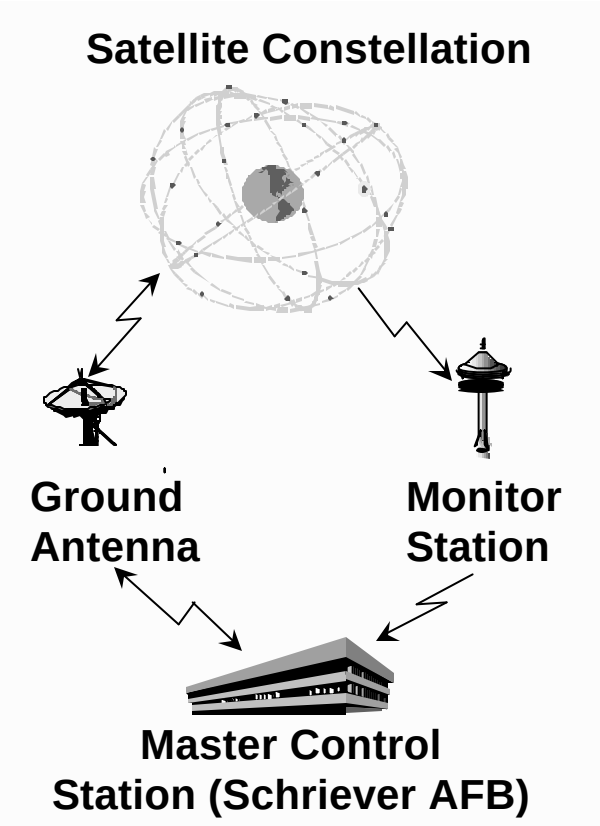
# High-G MEMs IMU Coordinated Development & Manufacturing Effort for Common Guidance

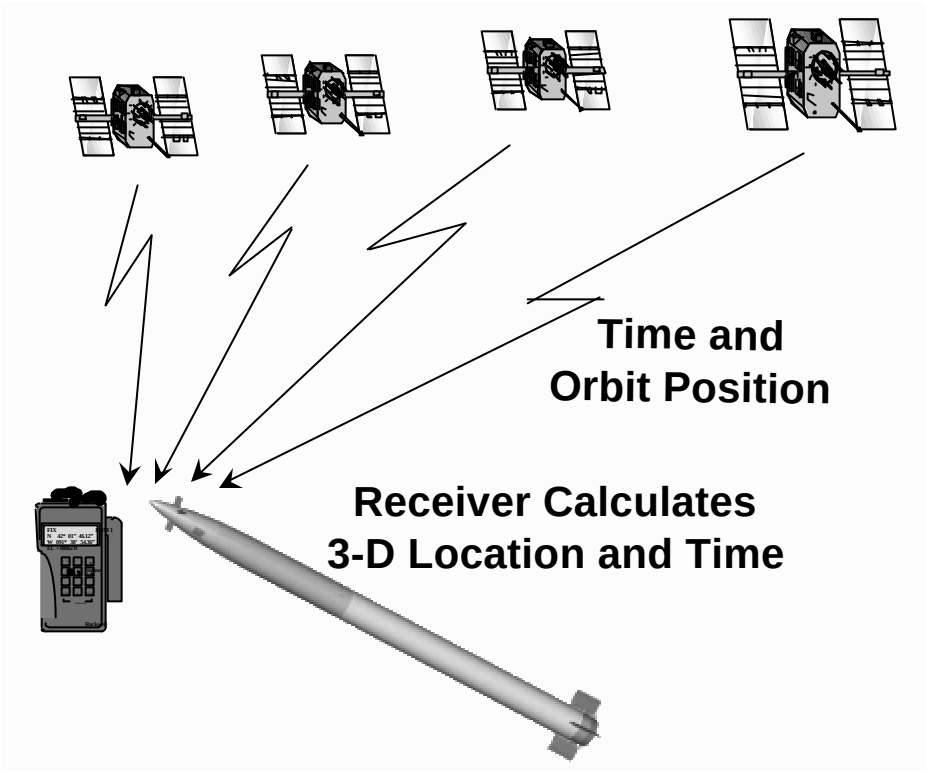
**(aka: Common Guidance – Common Sense Program)**




- **Purpose: To develop affordable and reliable G hardened, tactical grade, Common IMUs and GPS/ MEMS IMU for DoD Munitions, Missiles, Soldiers, Vehicles, and Aircraft**
- **Objective: Develop manufacturing technology for affordable, high-G IMU and IMU/GPS**
- **Approach: A joint Army/Navy managed effort that will achieve economy of scale and promote industry competition**

- **Global Positioning System (GPS)**
  - **Space-based radio navigation system consisting of 24 satellites in various inclined orbits**
  - **Provides an accurate, worldwide navigation and location capability**
  - **Large US and international military and commercial usage today**




- **GPS receivers measure their range and angle from 4, or more, satellites to infer receiver's latitude, longitude, altitude, time and velocity, with fixed accuracy**
  - **Civilian GPS Receivers provide 30 meters 3-D Location accuracy**
  - **Military GPS receivers provide 9 meters 3-D location accuracy**
  - **Jamming degrades or eliminates this capability**

# Why not INS only?

- **IMUs / INSs Require Initialization**
- **The IMU/INS Loose Initialization when Subjected to Moderate G Launch that Require Re-Initialization and Updates**
- **Initialization Requires Radar or GPS to Provide Position Information**
- **Unaided "INS Only" for Guided Munitions Would Require Hardened 0.01º/hr to 0.0001º/hr Accuracy for Extended Range Scenarios**

# Why not GPS only?

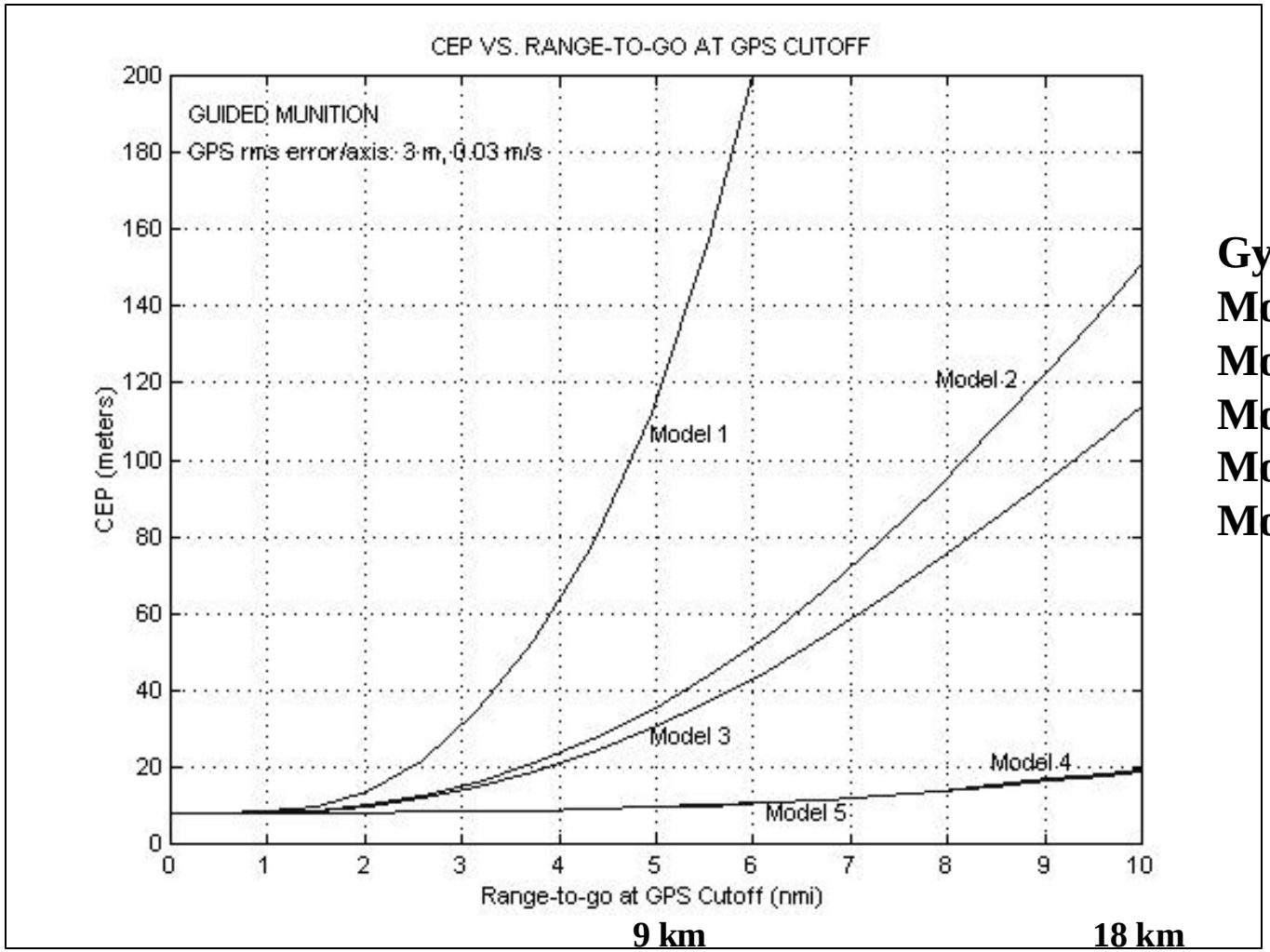
- **GPS is Susceptible to Many ECM Jamming Sources**
- **GPS Guided Munitions Require Vertical Reference for Maneuvering**
- **Jammed GPS Receivers Leave Munition Unguided**

# Why GPS and Inertial Together?

- **GPS Aids IMU Tracking by Continually Updating the IMU**
- **IMUs Deeply Coupled with GPS Adds Jamming Resistance**
- **If GPS Completely Jammed in Target Vicinity, the IMU will Complete Terminal Guidance**
- **GPS and IMUs are Mutually Aiding Systems**

COMMON GUIDANCE COMMON SENSE

# *What do those IMU Bias numbers mean to a munition?*

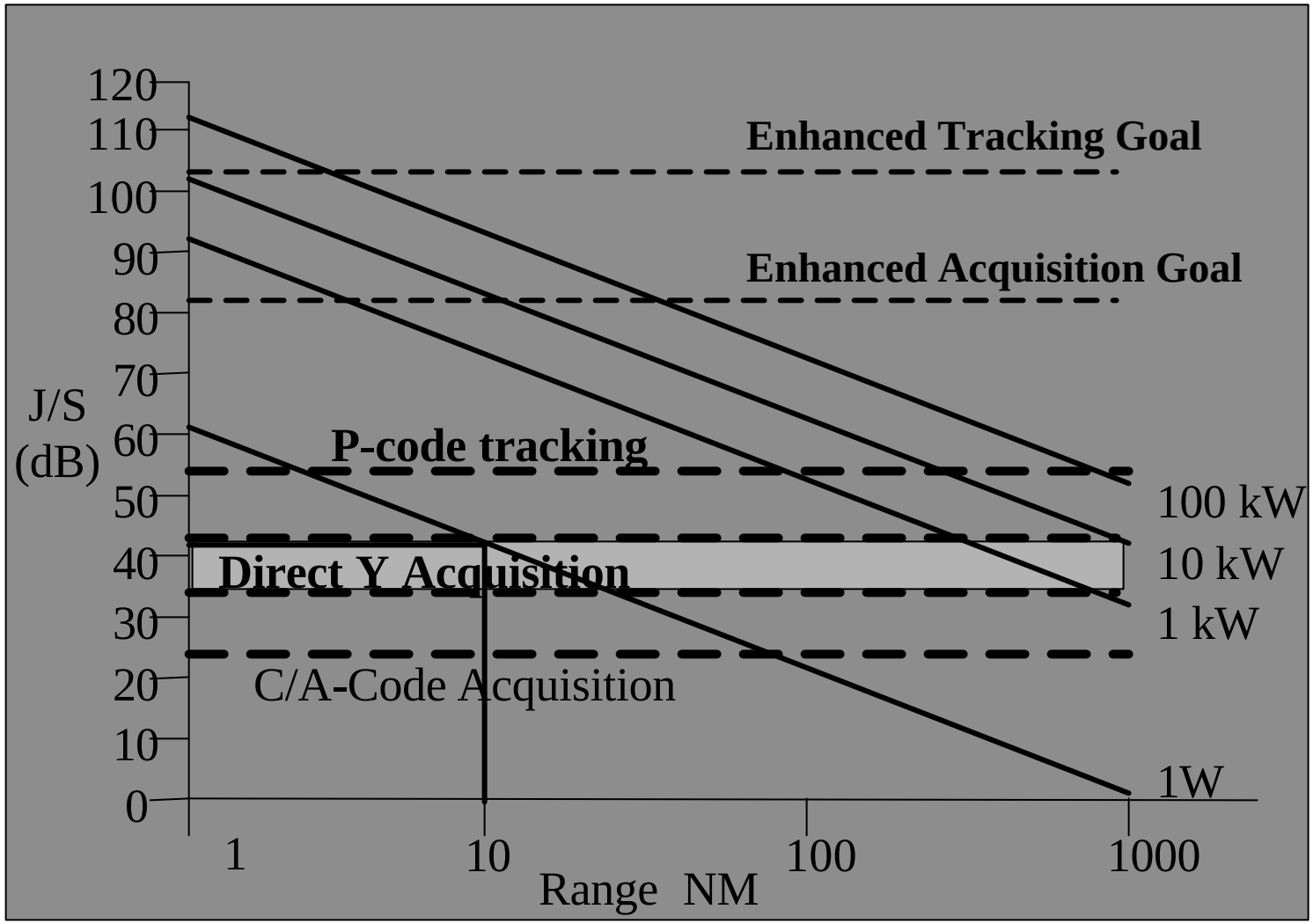



**9 km** **18 km**

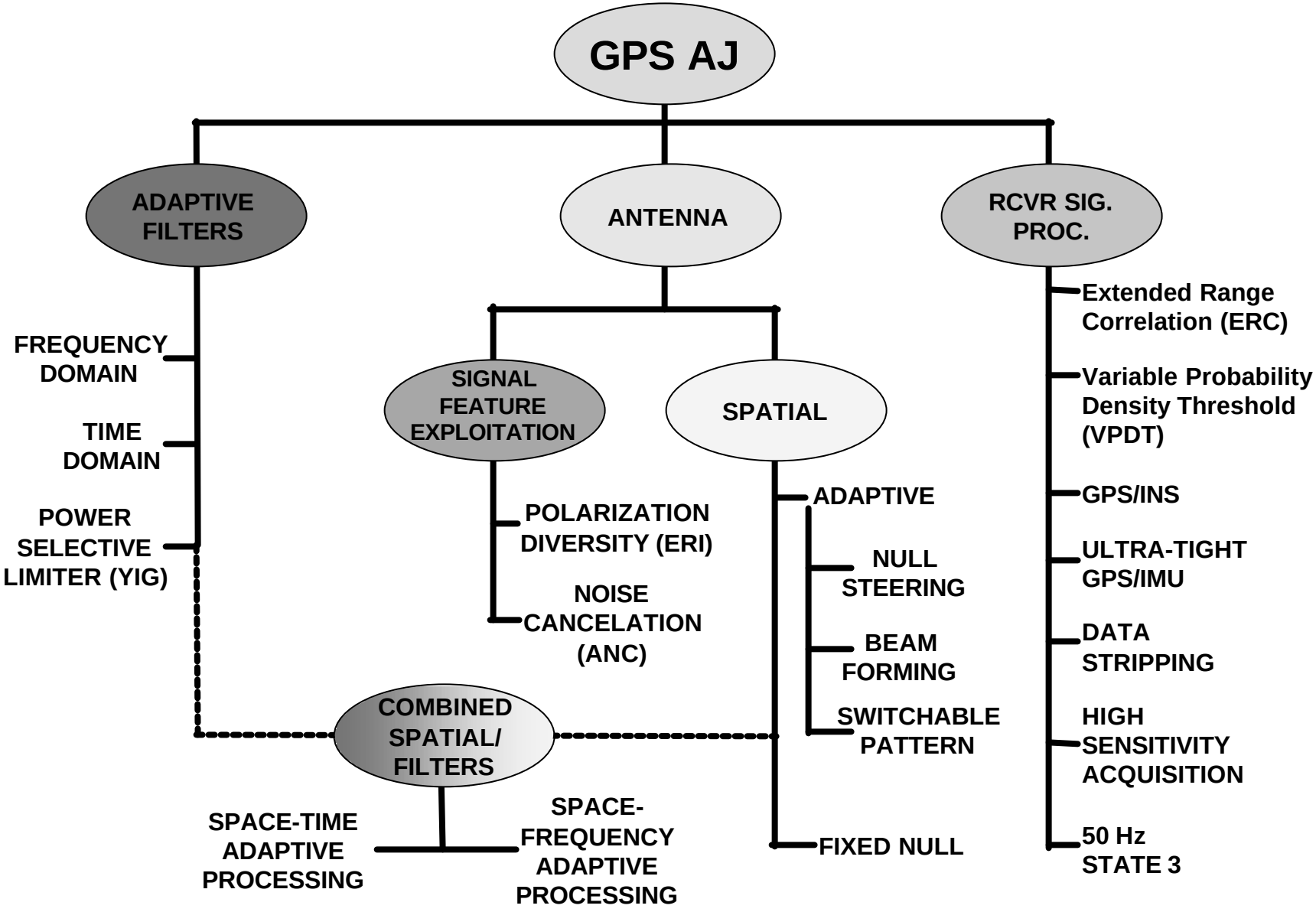
**Gyro Bias:**
**Model 1: 1000º/hr**
**Model 2: 50º/hr**
**Model 3: 10º/hr**
**Model 4: 1º/hr**
**Model 5: 0.1º/hr**

# GPS in Jamming Environment

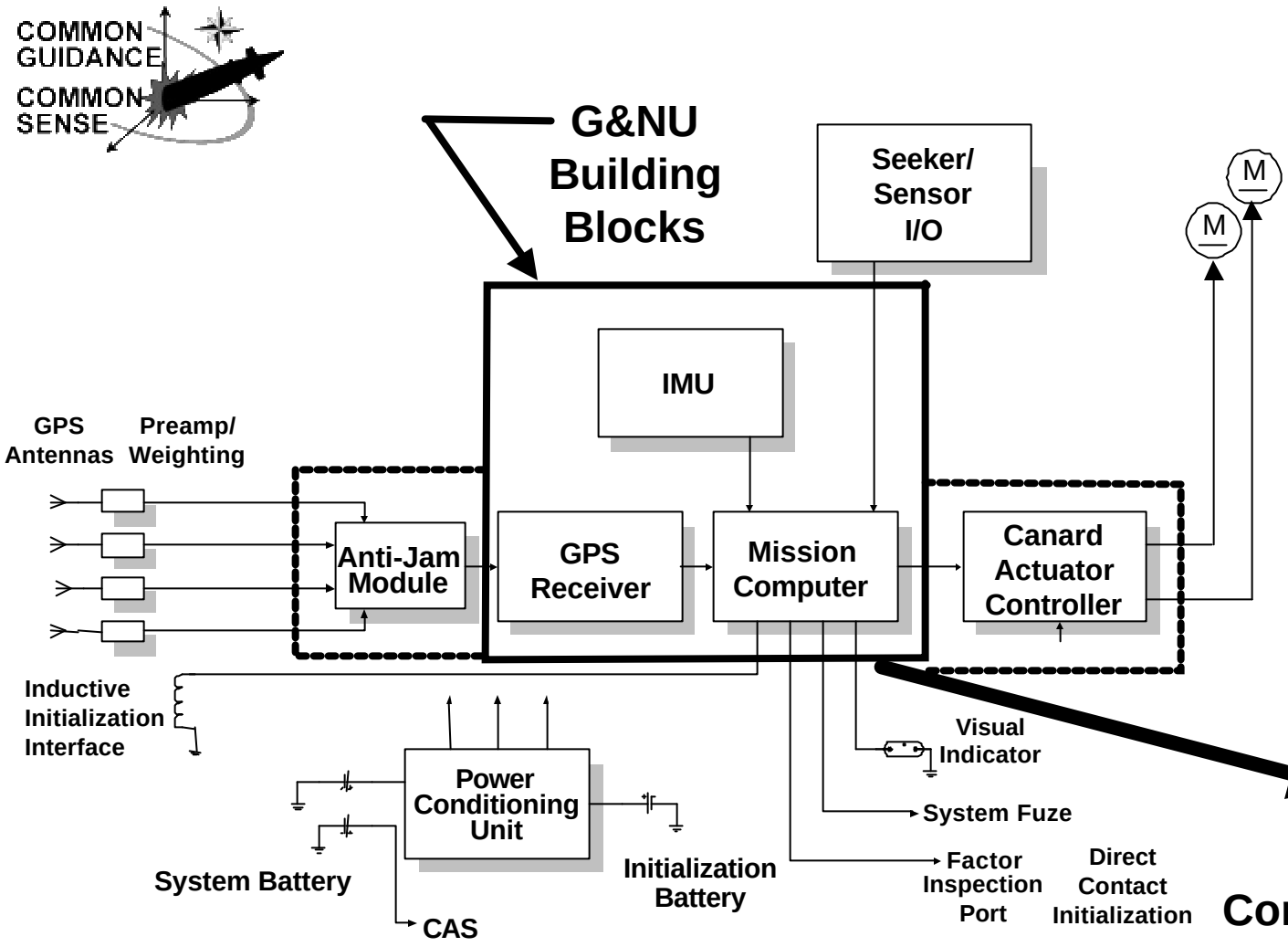
**Deeply Integrated GPS/IMU with Active Jammer Cancellation will Allow Precision Guided Munitions to Approach Most Targets UN-JAMMED!**



# Anti-Jam Techniques - The Family Tree



# Typical GN&C Functional Block Diagram




**Typical**
**As used in:**
**XM982, PGMM, GMLRS, LCCM, QuickLook, TERM, FCS Suite, AGS, ERGM, TCM**

***Building Block of the Future***

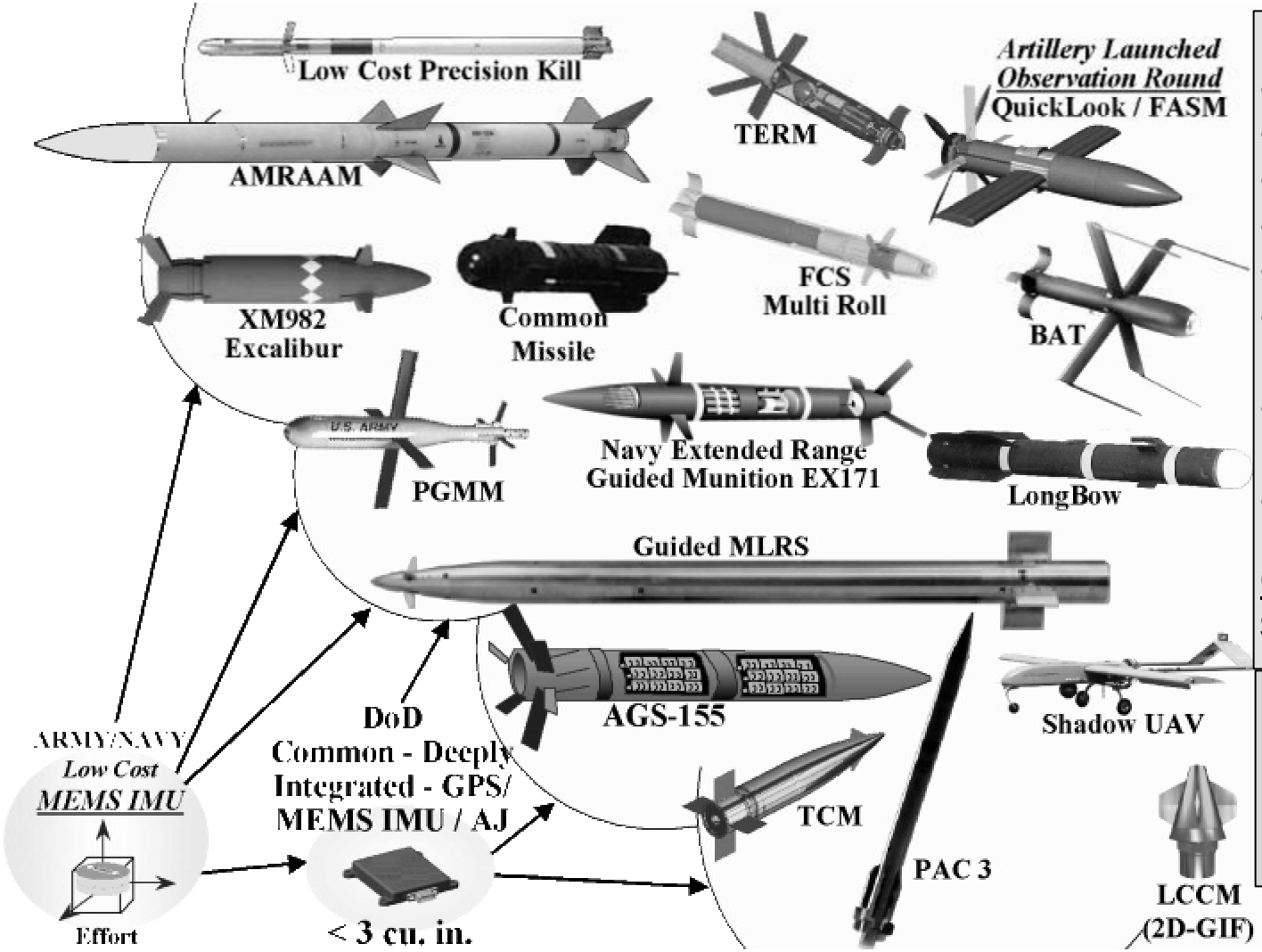
**Common Guidance & Navigation Unit (GNU) Module Single Processor Architecture**

**Currently, Each Subassembly Represents One or More Circuit Card Assemblies**

# Low Cost, High-G, MEMS, IMU & Common Guidance Coordinated Development and Manufacturing Effort

**(aka: Common Guidance – Common Sense (CGCS))**

***Objective:*** **Design, Develop and Establish Automated Manufacturing Technologies for Low Cost, Accurate, High-G MEMS IMUs and Common GPS/IMU/AJ Guidance.**




***Warfighter Payoffs:***

- **Reduce cost & size.**
- **System commonality.**
- **Increase Stowed Kills.**
- **Reduce Logistics.**
- **Improve Survivability.**
- **Reduce Collateral Damage.**
- **Minimize non-combatant casualties.**
- **Increase Lethality.**

**Cost Benefits (FY06-23)**
**$1,680,000K (Cost Avoidance)**

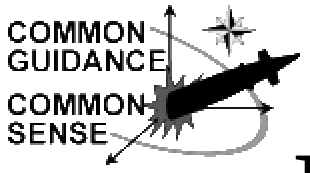
**Pacing Technologies:**

- **MEMS Inertial Sensors**

# Affordability Strategy Enablers

- **Joint S&T / MANTECH Management**
  - **Efficient and Effective**
- **Economy of Scale / Volume Business Strategy**
  - **One Common MEMS IMU System for > 90% of All DoD Applications**
    - **Reduces Unit Cost**
    - **Stabilizes and Extends Production Line Life**
    - **Reduced Maintenance and Repair Costs**
    - **Inter-Service interoperability**
  - **One Common DI-GPS/ISA System for > 90% of All DoD Applications**
- **Competition**
  - **Development: Enhances innovation and market stability**
  - **Production: Further reduces unit cost and improves quality**

**Goal: - Common MEMS Guidance for > 90% of all DoD Applications**




# Program / Business Strategy

- **Go To Multiple IMU Design / Manufacturing Teams Build to Common Requirement.**
  - **Work Design S&T and MANTECH Details Concurrently**
  - **Reduce Program Risks**
  - **Insure Competition in Development & Later Production**
  - **Ensures System Commonality / Interoperability**
- **Teams Leverage Process Improvements into multiple DoD Applications, which drives Affordability**
- **Teams Incorporate Common IMU into Common GPS/IMU/AJ Guidance & Navigation Unit built to DoD Common Guidance Spec and ICD**

# *Building Block of the Future*

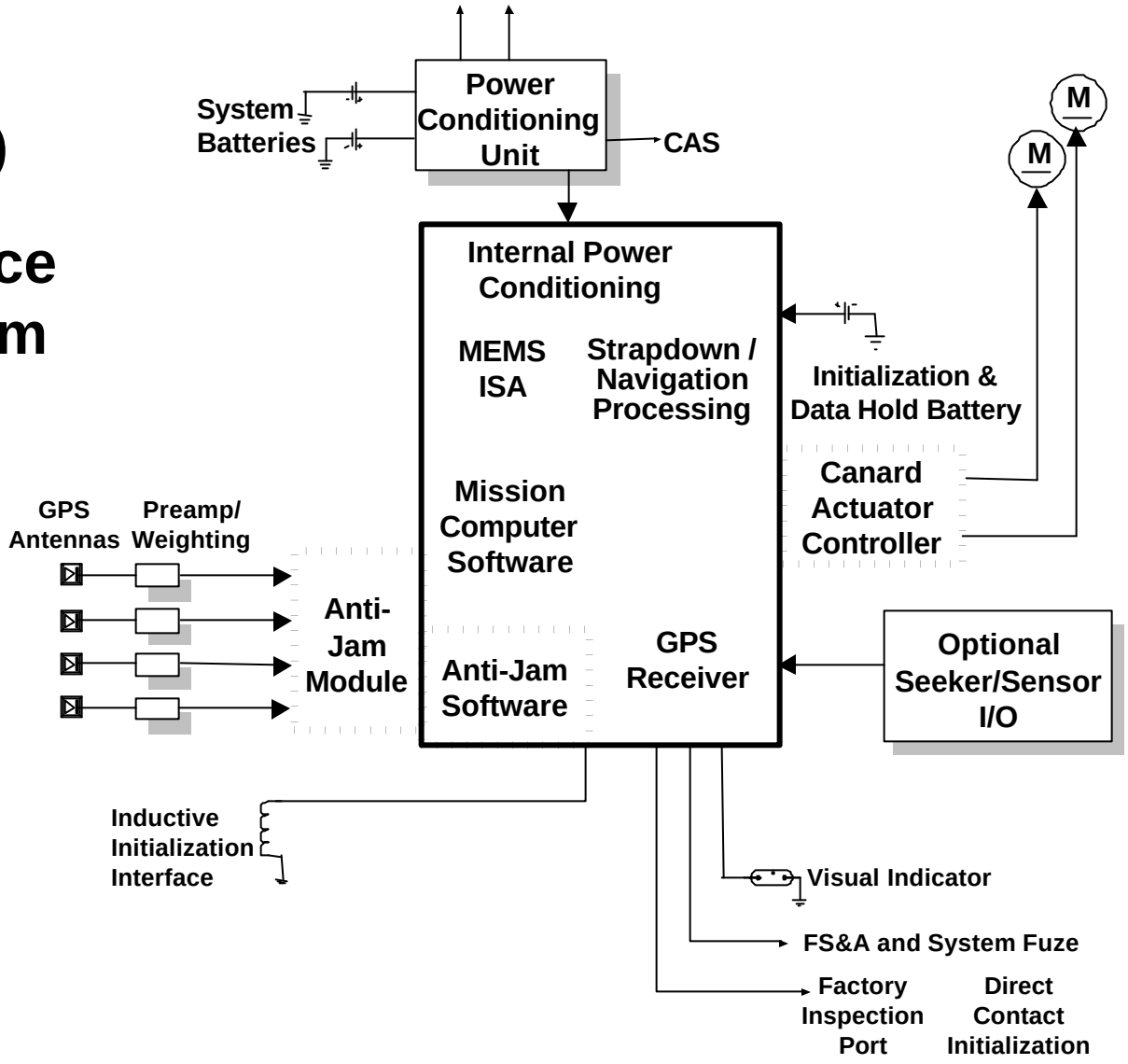
**Common Guidance & Navigation Unit (GNU)**

**Common G&N Interface Control (ICD) & System Specification**

**Deep Integration**

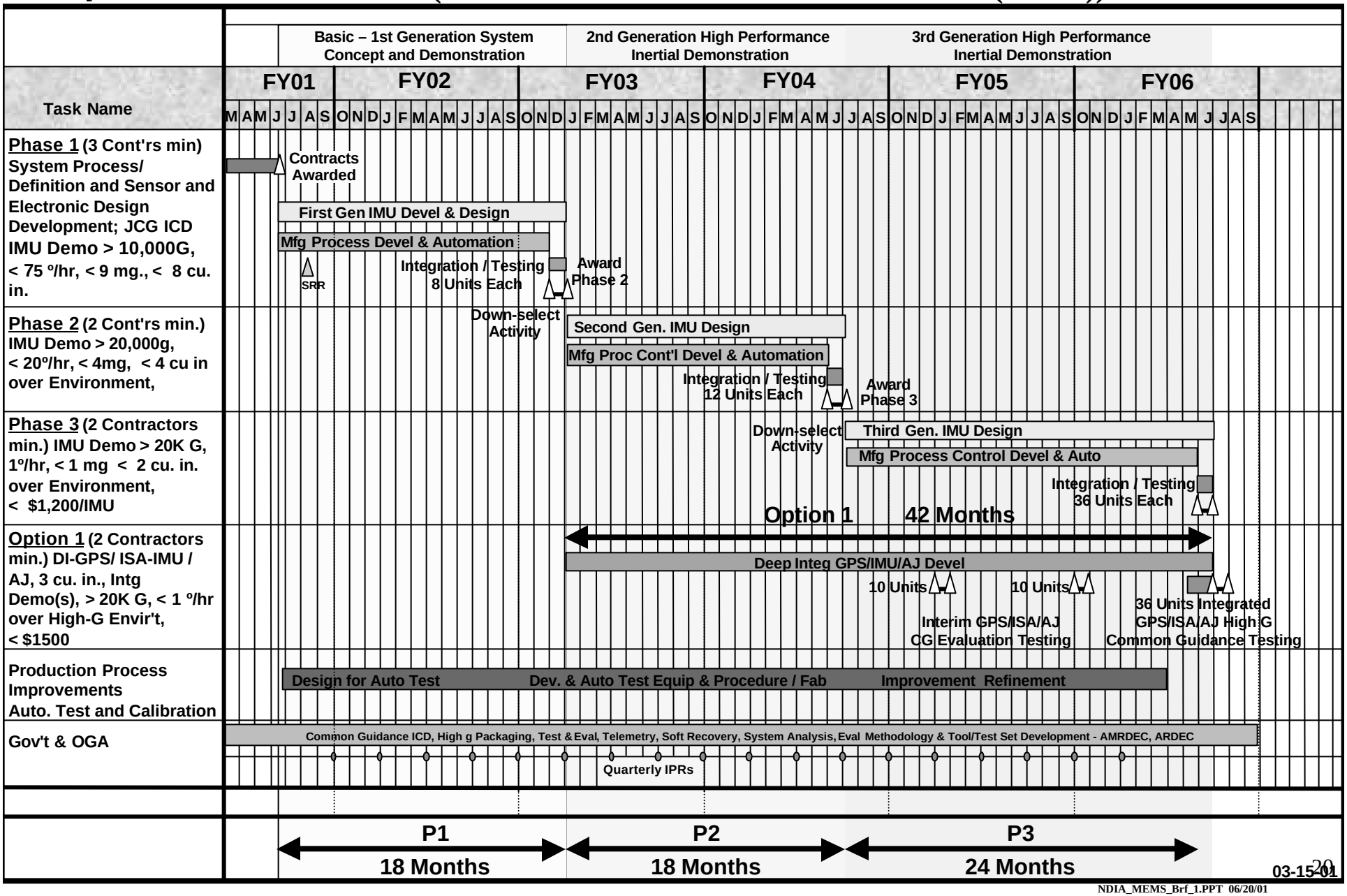
**Single Processor Architecture**

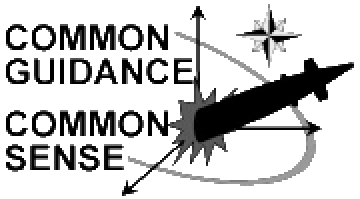
**Higher Reliability**
**Higher Prod. Volume**
**Multiple Vendors**
**Economy of Scale**
**Promotes Competition**
**Low Cost**



# High-G MEMs IMU Coordinated Development & Manufacturing Effort Schedule for Common Guidance

## (aka: Common Guidance – Common Sense (CGCS))






# Summary

- **Affordable, High-G, Accurate MEMS IMUs are required for next generation munitions, missiles and other G&N applications.**
- **The program described has a significant return for the investment across DoD.**
- **The program will develop 2 contractors capable of producing Low Cost MEMs IMU systems at < $1200/unit in production and DI-GNU systems at < $1500/unit in production.**